Western Boundary Time Series in the Atlantic Ocean.

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PROJECT SUMMARY

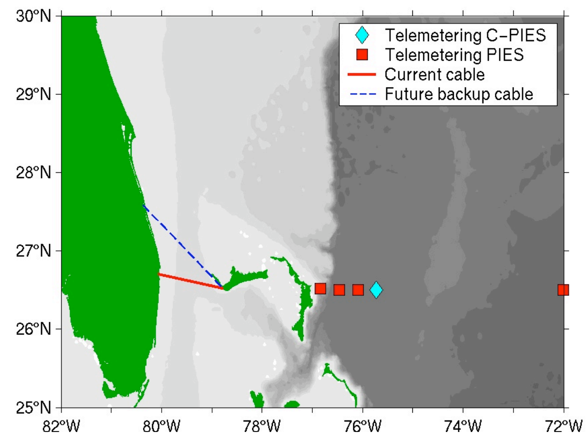

Figure 1: *Observational components of the Western Boundary Time Series project in the North Atlantic.*

In the subtropical North Atlantic, the meridional overturning circulation consists primarily of two western boundary components: the northward flowing Gulf Stream and the southward flowing Deep Western Boundary Current. The Gulf Stream is the strong surface intensified flow along the east coast of the United States that brings warms waters of tropical origin northward along the eastern seaboard of the United States. The Gulf Stream also brings with it carbon, nutrients and tropical fish. It supplies warm waters along the coast that impact a multitude of important climate phenomena including hurricane intensification, winter storm formation and moderate European weather. The Gulf Stream includes the bulk of what we call the 'upper limb' of the meridional overturning circulation in the subtropical Atlantic, in addition to a strong wind-driven flow. As the Gulf Stream flows northward it loses heat to the atmosphere until eventually, in the subpolar North Atlantic, some of the waters carried in the current become cold enough to sink to the bottom of the ocean. This cold deep water then flows southward along the continental slope of the eastern United States as the Deep Western Boundary Current, which represents the 'lower limb' of the meridional overturning circulation.

Along the east coast of Florida, the Gulf Stream is often referred to as the Florida Current and it is fortuitously confined within the limited bathymetric channel between Florida and the Bahamas Islands, thus making a long-term observing system both practical and cost effective. Similarly, the Deep Western Boundary Current is located within several hundred miles to the east of Abaco Island, Grand Bahamas. The convenient geometry of the Bahamas Island chain thus allows an effective choke point for establishing a long term monitoring program of both the upper and lower limbs of the overturning circulation.

This project consists of two components to monitor the western boundary currents in the subtropical Atlantic: *<u>Task 1:</u>* Real-time Florida Current transport measurements using a submarine telephone cable and calibration cruises, *<u>Task 2:</u>* Deep Western Boundary Current water property measurements using dedicated research ship time and quasi-real-time transport monitoring using moored instruments.

Task 1: Continuous Transport measurements of the Florida Current

The project maintains NOAA's well-established and climatically significant Florida Current volume transport time series. Over 25 years of daily mean voltage-derived transports have been obtained for the Florida Current using out-of-service and in-use cables spanning the Straits of Florida. The cable voltages can be converted to physically meaningful transport estimates i.e., intensity of the flow, using electromagnetic induction theory. These transport measurements contain interannual and decadal changes on the order of 10% of the long-term mean transport, and during some periods the decadal changes track the North Atlantic Oscillation Index. The strong correlation of Florida Current transport variability with the North Atlantic Oscillation, and by extension with the large-scale sea-surface temperature patterns associated with the North Atlantic Oscillation, suggests connections to tropical Atlantic variability on climatically significant time scales. These strong correlations also link the Florida Current transport with the numerous significant weather and climate phenomena that are related through large-scale ocean-atmosphere patterns in the Atlantic, including decadal and inter-decadal variations in fisheries, rainfall, and hurricane activity.

Funding provides for continuous collection of cable voltages (each minute) and automated removal of geomagnetic noise. In addition to the cable measurements, regular calibration cruises are required for this project's success. These measurements are funded through a complementary project that measures the upper ocean thermal structure in the Atlantic through high-density VOS XBT observations. Funding from the high-density XBT program provides for four two-day small charter boat calibration cruises on the R/V F. G. WALTON SMITH each year and eight one-day charters onboard small fishing vessels, provided sufficient ship-time is available.

Task 2: Deep Western Boundary Current Time Series

Over the past 20+ years a variety of snapshot sections and time series mooring arrays have been placed along the continental slope east of Abaco Island, Grand Bahamas, in order to monitor variability of the transport carried by the Deep Western Boundary Current. The Abaco time series began in August 1984 when the NOAA Subtropical Atlantic Climate Studies Program extended its Straits of Florida program to include measurements of western boundary current transports and water mass properties east of Abaco Island, Grand Bahamas. Since 1984, more than 20 hydrographic sections have been completed east of Abaco, most including direct velocity observations, and salinity and oxygen bottle samples. Many sections have also included measurements of carbon, chloroflourocarbon, and other water mass tracers.

The repeated hydrographic and tracer sampling at Abaco has established a high-resolution, high quality record of water mass properties in the Deep Western Boundary Current at 26.5ºN. Events such as the intense convection period in the Labrador Sea and the renewal of classical Labrador Sea Water in the 1980's are clearly reflected in the cooling and freshening of the Deep Western Boundary Current waters off Abaco with the arrival of a strong chlorofluorocarbon pulse approximately 10 years later. This data set is unique in that it is not a single time series site but in instead a time series of transport sections, including high quality water property measurements, of which very few are available in the ocean that approach even one decade in length. This task includes annual cruises across the DWBC to measure the water mass properties and transports. With the cooperation of University of Miami researchers (Drs. Johns and Beal) and funding from the National Science Foundation for the Meridional Overturning Circulation and Heat transport Array (MOCHA), and sharing of personnel and ship-time resources, these cruises have been conducted twice each year since 2004. This level of sampling will continue through 2014.

Also starting in 2004, a new component was added to the project consisting of a low-cost monitoring system that provides an hourly time-series of the magnitude of the Deep Western Boundary Current mass transport in quasi-real-time (downloaded to research ships twice each year). This new monitoring system includes a moored array of Inverted Echo Sounders (IESs), and each instrument is additionally equipped with a bottom pressure gauge (PIES) and in one case a bottom current meter (CPIES). The line of PIES/CPIES moorings stretches across the shallow northward flowing Antilles Current as well as the southward flowing Deep Western Boundary Current. The IES monitoring system will also be compared to a series of measurement systems that have been deployed as part of an interagency and international partnership that is testing a variety of low cost methods for observing the complete meridional overturning circulation cell at 26.5ºN in the Atlantic (e.g. MOCHA and the United Kingdom's Rapid Climate Change Program).

Continued time series observations at Abaco are seen as serving three main purposes for climate variability studies:

- Monitoring of the DWBC for water mass and transport signatures related to changes in the strengths and formation regions of high latitude water masses in the North Atlantic for the ultimate purpose of assessing rapid climate change.
- Serving as a western boundary endpoint of a subtropical meridional overturning circulation (MOC)/heat flux monitoring system designed to measure the interior dynamic height difference across the entire Atlantic basin and its associated baroclinic heat transport.
- Monitoring the intensity of the Antilles Current as an index (together with the Florida Current) of interannual variability in the strength of the subtropical gyre.

The Western Boundary Time Series project is one component of the NOAA "Ocean Reference Station" system in the Atlantic Ocean, and it specifically addresses the NOAA climate goals by providing long term integrated measures of the global thermohaline (overturning) circulation. This project is designed to deliver yearly estimates of the state of the thermohaline circulation, i.e. its intensity, properties, and heat transport. Heat and carbon generally are released to the atmosphere in regions of the ocean far distant from where they enter. Monitoring the transport within the ocean is a central element of documenting the overturning circulation of fresh water, heat and carbon uptake and release. Long-term monitoring of key choke points, such as the boundary currents along the continents including the Gulf Stream and the Deep Western Boundary Current, will provide a measurement of the primary routes of ocean heat, carbon, and fresh water transport and hence include the bulk of the Meridional Overturning Circulation.

Project web sites:

http://www.aoml.noaa.gov/phod/floridacurrent/
http://www.aoml.noaa.gov/phod/wbts/

FY 2007 PROGRESS

Task 1: Continuous transport of the Florida Current

Recording instruments are located at Eight Mile Rock, Grand Bahamas Island. At Eight Mile Rock and in West Palm Beach, Florida, electrode equipment is in place, securing a stable reference voltage (i.e. grounds) at either end of the submerged telephone cable owned by AT&T. The monitored cable can be seen in Figure 2, stretching across the Florida Straits. Data acquisition has continued without significant incident although during the period from January 2007 through October 2007 there was a slight low-bias in the cable transports relative to the dropsonde cruise data. This offset has been traced to a failure in one of the anodes (Earth ground), and it is expected that the data will be completely recoverable with additional processing during early FY08. This FY has seen the continued success of the stable system of processing and quality control for both the calibration section data and the cable transport data implemented in FY05. Cable voltages are recorded every minute, and are post processed to form daily transport estimate. The Table 1 below shows the number of hourly averaged voltage measurements.

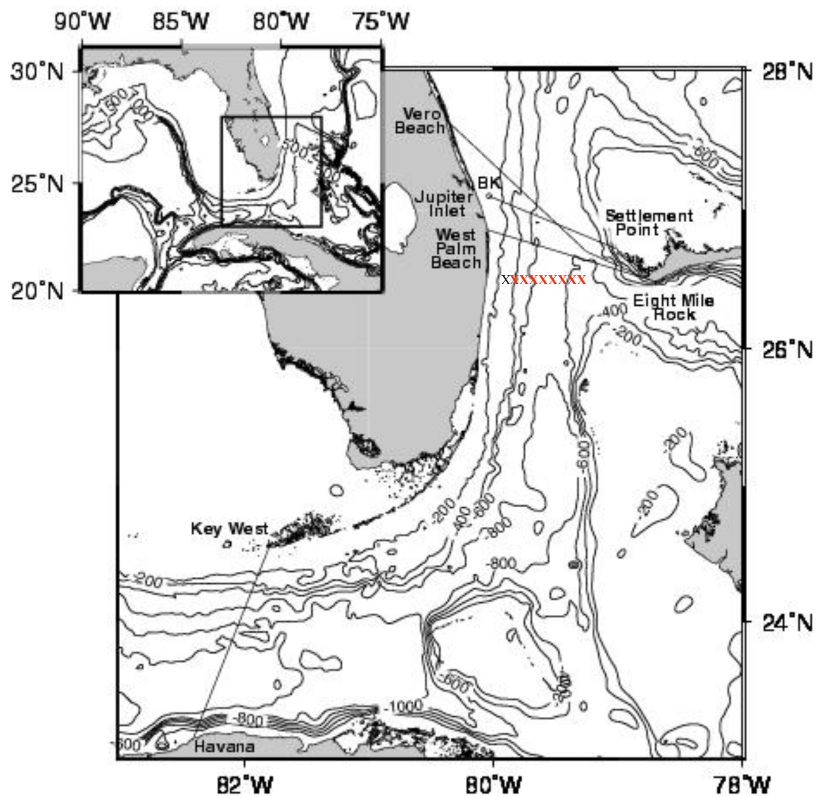

Figure 2: *Location of submarine telephone cables (solid black) and nine stations (red) occupied during calibration cruises.*

FY 2007	FY 2006	FY 2005	FY 2004	FY 2003
100% Return[1]	98% Return	88% Return[2]	87% Return[2]	89% Return

Table 1: Data return from continuous cable voltages (% Return based on the maximum number of days possible in one year: e.g. 365 for non-leap years and 366 for leap years like 2004).

Planned Cruise	FY 2007	FY 2006	FY 2005	FY 2004	FY 2003
1	13-Dec-2006	11-Nov-2005	19-Nov-2004 dropsonde lost	9-Dec-2003	clearance problems
2	15-Dec-2006	17-Nov-2005	29-Nov-2004	16-Dec-2003	clearance problems
3	29-Mar-2007	2-Feb-2006	17-Feb-2005	9-Jan-2004	equipment problems
4	19-Jun-2007	14-Mar-2006	24-Feb-2005 section incomplete due to weather	13-Jan-2004 – GPS failure on two stations	18-Mar-03
5	10-Jul-2007	27-Mar-2006	18-May-2005	7-May-2004	June 7, 2003 – dropsonde failure
6	5-Sep-2007, dropsonde electronics problems	22-Jun-2006	21-Jun-2005 dropsonde lost	24-May-2004	no dropsonde
7	27-Sep-2007	30-Jun-2006	31-Aug-2005	Jun 7, 2004	no dropsonde
8	Postponed to early FY08 due to weather	20-Jul-2006		Jun 11, 2004	no dropsonde
9		15-Sep-2006		Aug 24, 2004	
10				1-Sep-2004 - GPS antenna failure	
	87.5% successful	100% successful	50% successful[3]	100% successful[4]	13% successful[5]

Table 2: Cruise dates for 1-day small boat calibration cruises using dropsonde instrument.

[1] Presuming January – September time period is successfully corrected for the small observed bias, which is likely.
[2] Note a pair of hurricanes destroyed the recording equipment and damaged the infrastructure in Sept. 2004.
[3] Final cruise postponed to next fiscal year due to weather/scheduling issues. Two dropsonde instruments were lost due to equipment malfunctions. One cruise was only partially completed due to weather.
[4] Two additional cruises were planned for FY04 due to dropsonde failures in FY03.
[5] Sections missing due to: dropsonde failure (4) and clearance problems (2).

Small charter boat calibration trips

A total of seven 1-day surveys were conducted using a dropsonde profiler (the final cruise has been postponed to the next FY due to weather). Measurements are taken at nine stations along 27ºN and include vertically averaged horizontal velocity, surface velocity and expendable temperature probes (XBTs). The cruise dates are shown in Table 2. Some electronic failures of the dropsonde resulted in some lost data for one cruise. This equipment failure, plus the retirement of key engineering staff has necessitated the complete redesign of the dropsonde system to be completed in FY2008.

Full Water Column calibration cruises:

Two-day cruises on RV Walton Smith are generally scheduled four times per year. Sufficient ship-time funds for only three of the cruises were provided in FY07 (the final cruise of FY07 was postponed into early FY08 due to ship availability). All cruises include nine stations with full water column CTD, lowered ADCP, and continuous shipboard ADCP. The station locations are shown in Figure 2. Table 3 below includes the cruise dates and number of water samples taken for oxygen concentration (O2) and salinity (S).

FY2007		FY2006		FY 2005		FY 2004		FY 2003	
Date	Samples	Date	Samples	Date	Samples	Date	Samples	Date	Samples
Dec 13-14, 2006	60 O2, 48 S	Dec 14-16, 2005	60 O2, 48 S	Dec 3-4, 2004	58 O2, 44 S	Jan 8-9, 2003	55 O2, 46 S	Nov 19-20, 2002	43 O2, 44 S
Jun 28-29, 2007	60 O2, 48 S	Jan 29-31, 2006	60 O2, 48 S	Jun 3-4, 2005	58 O2, 45 S	May 6-7, 2004	47 O2,	Mar 21-22, 2003	59 O2, 49 S
Oct 4-5, 2007	60 O2, 48 S	Jun 25-27, 2006	60 O2, 48 S	Jul 11-12, 2005	58 O2, 45 S	Jul 4-5, 2004	56 O2,	July 2-3, 2003	56 O2, 46 S
		Sep 18-19, 2006	68 O2, 48 S	Nov 20-23, 2005	60 O2, 48 S	Aug 27-28, 2004	55 O2, 42 S	Oct 2-3, 2003	57 O2, 43 S
75% of planned cruises completed		100% of planned cruises completed		100% of planned cruises completed		100% of planned cruises completed		100% of planned cruises completed	

Table 3: Cruise dates for 2-day calibration cruises on the R/V Walton Smith. Note FY2005: The last cruise planned for in FY 2005 was postponed for early FY 2006. Note FY 2007: Only three cruises were completed due to lack of ship-time charter funds.

Task 2: Deep Western Boundary Current time series

Two full-water-column cruises of CTD, lowered ADCP, and shipboard ADCP were conducted during FY07 within the Florida Straits and east of Abaco Island, Bahamas on the NOAA Ship Ronald H. Brown. At each station, a package consisting of a Seabird Electronics Model 9/11+ CTD O_2 system, an RDI 150 kHz Workhorse Lowered Acoustic Doppler Current Profiler, a RDI 300 kHz Workhorse Lowered Acoustic Doppler Current Profiler, and 23 10-liter Niskin bottles, was lowered to the bottom. This provided profiles of velocity, pressure, salinity (conductivity), temperature, and dissolved oxygen concentration. Water samples were collected at various depths and analyzed for salinity and oxygen concentration to aid with CTD calibration.

The first hydrographic cruise this year took place on the NOAA Ship Ronald H. Brown during Mar 22-Apr 10, while the second took place during Sept 11-22. (The latter cruise was scheduled to begin on Sep 8, however the Brown was unable to sail on time due to an insufficient number of engineers for safe manning of the vessel; this delay in sailing resulted in the loss of about 10% of the planned CTD stations.) The stations were occupied at the locations shown in Figure 3. Table 4 lists the cruise dates and bottle samples taken compared to previous years. Five inverted echo sounders (IES) sites were maintained as shown in Figure 3 including: four IES with pressure sensors (PIES) and one IES with pressure sensor and bottom current meter (CPIES). Four additional temporary IES/PIES sites were deployed during the September 2006 cruise between the permanent sites to test array resolution.

FY	Date	Stations	Bottle Samples	Comments
2007	Sep, 2007	48	737 O2, 706 S	Telemetry data collected from five PIES/CPIES
2007	Mar, 2007	74	1092 O2, 1135 S	Telemetry data collected from five PIES/CPIES
2006	Sep, 2006	42	465 O2, 568 S	2 IES recovered, 1 IES lost (but data retrieved via telemetry), 7 IES deployed, and data retrieved via telemetry from 2 IES
2006	Mar, 2006	72	921 O2, 943 S, 391 nut., 506 DOC/TOC, 80 DIC, 40 TALK	2 IES recovered, 2 IES deployed, data from 3 IES recovered via acoustic telemetry
2005	Sep, 2005	53	728 O2, 728 S	1 IES deployed, 2 IESs recovered, data from 3 IESs recovered via acoustic telemetry
2005	May, 2005	70	1084 O2, 1180 S	1 IES deployed, data recovered from 3 IESs via acoustic telemetry
2004	Sep, 2004	42	634 O2, 629 S	5 IES mooring deployments
2003	Feb, 2003	54	844 O2, 843 S	3 IES Mooring recoveries, Short Seabeam in Florida Straits
2002	June 2002	57	924 O2, 924 S	Extended Seabeam survey east of Abaco Island, SF6 samples.
2001	April 2001	33	607 O2, 659 S	4 IES mooring deployments

Table 4: Cruise dates and water samples taken for Large Vessel full water column surveys of the Deep Western Boundary Current. September 2006 cruise aboard the R/V Seward Johnson and May 2005 cruise aboard the R/V Knorr with ship time funded by NSF. April 2001 cruise on the R/V Oceanus. All other cruises were conducted on the R/V Ronald H. Brown. Additional nutrient and carbon measurements that were taken during the March 2006 cruise were collected using base funds. Funding for collection in future years is being requested as an Add Task.

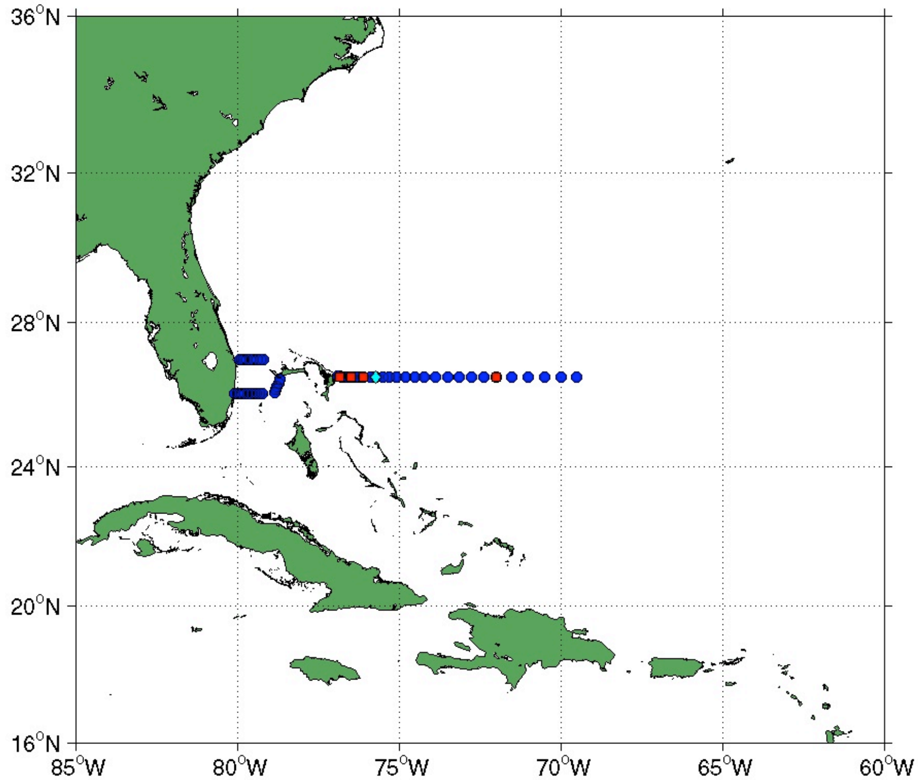

Figure 3: *Approximate locations of full water column hydrographic stations sampled on the two cruises in FY 2005. Blue circles denote CTD sites. Red squares denote PIES moorings and the cyan diamond denotes a CPIES mooring. Note the five CTD stations east of 72°W were not occupied during the September 2007 cruise due to time constraints that resulted from a departure delay as a result of insufficient staffing for the Brown engineering department.*

Research highlights

1. Numerous climate models have shown that variations in the Meridional Overturning Cell could have significant climate impacts over a wide range of locations around the globe. We compared the use of bottom pressure gauges and inverted echo sounders to a more traditional picket fence of current meters and showed that the far less expensive option of using bottom pressure and inverted echo sounders was able to reproduce the transport fluctuations observed by the current meter arrays well (Meinen et al., 2004; 2006). This has led to a more efficient, lower cost monitoring system (now funded through the NOAA Office of Climate Observations) for the lower limb of the meridional overturning circulation.

2. A recent publication (Meinen et al., 2006) utilizing the PIES/C-PIES mooring data has shown that there is no significant trend in the components of the meridional overturning cell near the western boundary over the past twenty years. Furthermore these results demonstrate that the baroclinic and barotropic components of the transport variability are partially compensating one another,

indicating that monitoring of MOC transport variations via hydrographic sections is more inherently problematic than had previously been known.

3. Two publications in the journal ***Science*** appeared using the data from this program in concert with the observations made by the international MOCHA/RAPID array (Cunningham et al., 2007; Kanzow et al., 2007). These papers demonstrated that the first year of data from the joint US/UK array is capturing the net MOC transport across 26.5°N with a high degree of accuracy. The papers also demonstrate that the MOC is more highly variable at time scales of weeks to months than had previously been assumed.

Peer Reviewed Publications:

1. Cunningham, S. A., T. Kanzow, D. Rayner, M. O. Baringer, W. E. Johns, J. Marotzke, H. R. Longworth, E. M. Grant, J. J-M. Hirschi, L. M. Beal, C. S. Meinen, and H. L. Bryden, "Temporal Variability of the Atlantic Meridional Overturning Circulation at 26.5°N", *Science*, 317, 935, DOI: 10.1126/science.1141304, 2007.
2. Kanzow, T., S. A. Cunningham, D. Rayner, J. J-M. Hirschi, W. E. Johns, M. O. Baringer, H. L. Bryden, L. M. Beal, C. S. Meinen, and J. Marotzke, "Observed flow compensation associated with the Meridional Overturning at 26.5°N in the Atlantic", *Science*, 317, 938, DOI: 10.1126/science.1141293, 2007.
3. Baringer, M. O., and C. S. Meinen, "The Meridional Overturning Circulation and Oceanic Heat Transport", in "Supplement to State of the Climate in 2006", A. Arguez, ed., *Bulletin of the American Meteorological Society*, 88(6), s1-s135, doi:10.1175/BAMS-88-6-StateoftheClimate, 2007.
4. Meinen, C. S., M. O. Baringer, and S. L. Garzoli. "Variability in Deep Western Boundary Current transports: Preliminary results from 26.5ºN in the Atlantic". *Geophysical Research Letters*, 33, L17610, doi:10.1029/2006GL026965, 2006.

Abstracts/Meeting Proceedings:

1. Bryden H., S. Cunningham, T. Kanzow, D. Rayner, M. Baringer, W. Johns, J. Marotzke, H. Longworth, E. Grant, J. Hirschi, L. Beal, C. Meinen, Circulation at 25°N, 2007. (IUGG XXIV General Assembly, July 2-13, Perugia, Italy.)
2. Cunningham, S. A., T. O. Kanzow, D. Rayner, M. O. Baringer, W. E. Johns, J. Y. Marotzke, J. J.-M. Hirschi, L. M. Beal, C. S. Meinen, H. L. Bryden, H. R. Longworth, E. M. Grant, Monitoring the Atlantic Meridional Overturning Circulation at 26.5°N, 2007. (RAPID Annual Meeting 2007, June 18-20, Plymouth, United Kingdom.)
3. Kanzow, T., S. Cunningham, J. Hirschi, D. Rayner, J. Marotzke, C. Meinen, W. Johns, M. Baringer, H. Bryden, L. Beal, Origin and dynamics of intra-seasonal variability of the meridional overturning circulation observed at 26.5°N, 2007. (RAPID Annual Meeting 2007, June 18-20, Plymouth, United Kingdom.)
4. Rayner, D., S. A. Cunningham, T. O. Kanzow, H. L. Bryden, J. J.-M. Hirschi, J. Y. Marotzke, W. E. Johns, L. M. Beal, M. O. Baringer, C. S. Meinen, Status of

the transatlantic mooring array at 26.5°N - Spring 2007, 2007. (RAPID Annual Meeting 2007, June 18-20, Plymouth, United Kingdom.)

5. Meinen, C. S., M. O. Baringer, and S. L. Garzoli, Variability in the Atlantic Meridional Overturning Circulation: Latest results from the NOAA Western Boundary Time Series project, 2007. (Office of Climate Observations Annual Review, June 5-7, Silver Spring, Maryland.)
6. Meinen, C. S., D. S. Luther and M. O. Baringer, Evolution of the Gulf Stream structure, transport, and vertical coherence from the Straits of Florida to the Southeast Newfoundland Ridge, 2007. (Office of Climate Observations Annual Review, June 5-7, Silver Spring, Maryland.)
7. Johns, W., S. Cunningham, T. Kanzow, H. Bryden, J. Marotzke, M. Baringer, L. Beal, C. Meinen, J. Hirschi, D. Rayner, Variability of the Atlantic meridional overturning circulation during 2004-2005 as observed from the 26°N RAPID-MOC Array, 2007. (AGU Joint Assembly, May 22-25, Acapulco, Mexico.)
8. Meinen, C. S., D. S. Luther, and M. O. Baringer, Evolution of the Gulf Stream structure, transport, and vertical coherence from the Straits of Florida to the Southeast Newfoundland Ridge, 2007. (EGU General Assembly, April 15-20, Vienna, Austria.)
9. Baringer, M. O., Heat transport variations in the subtropical North Atlantic. (Rapid Climate Change International Conference, October 24-27, 2006, Birmingham, United Kingdom.)
10. Meinen, C. S., M. O. Baringer, and S. L. Garzoli, Variability of the Western Boundary Currents in the subtropical North Atlantic. (Rapid Climate Change International Conference, October 24-27, 2006, Birmingham, United Kingdom.)
11. Longworth H. R., H. L. Bryden, M. O. Baringer: Variability in the Atlantic Meridional Overturning Circulation at 25ºN from 1980 to 2005. (Rapid Climate Change International Conference, October 24-27, 2006, Birmingham, United Kingdom.)
12. Cunningham, S., H. Bryden, J. Hirschi, D. Rayner, J. Marotzke, W. Johns, M. Baringer, C. Meinen: Vertical compensation of mass transports associated with the meridional overturning circulation in the Subtropical North Atlantic. (Rapid Climate Change International Conference, October 24-27, 2006, Birmingham, United Kingdom.)
13. Bryden, H. L., T. O. Kanzow, H. R. Longworth, S. A. Cunningham, M. O. Baringer, L. M. Beal, J. J.- M Hirschi, W. E. Johns, C. S. Meinen, J. Marotzke, D. Rayner, Variability in the Atlantic meridional overturning circulation at 25°N. (Rapid Climate Change International Conference, October 24-27, 2006, Birmingham, United Kingdom.)
14. Rayner D., S. Cunningham, H. Bryden, T. Kanzow, J. Hirschi, J. Marotzke, W. Johns, M. Baringer, C. Meinen, L. Beal: Evolution and maintenance of the transatlantic mooring array at 26.5°N. (Rapid Climate Change International Conference, October 24-27, 2006, Birmingham, United Kingdom.)